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Note

Europa's neutral cloud: morphology and comparisons to Io

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Abstract

Ground based observations of sodium escaping from Europa suggest the presence of an extended cloud of neutrals orbiting Jupiter. Using a Monte Carlo model we show that the large scale morphology differs from the sodium cloud at Io. At Europa, the trailing cloud is brighter and more extended than the leading cloud. We then use our results to consider the morphology of Europa's oxygen cloud.

Keywords: Satellites of Jupiter; Europa; Satellites, atmospheres; Atmospheres, dynamics

1. Introduction

The existence of a sub-surface ocean at Europa and the possibility of its sustaining life is one of the most exciting scientific questions of our time. Unfortunately, the remoteness of the satellite makes it difficult to study this ocean directly. Instead other markers must be found which point to the structure and composition of the ocean and which suggest the presence of biological markers. Studies of the atmosphere and atmospheric escape can provide clues needed for understanding Europa's icy shell and sub-surface ocean. The composition and energy distribution of material escaping from Europa are indicative of the interaction between its surface and the local plasma. Observations of this material made from Earth can provide insight into Europa's surface composition and interior and will help determine the capabilities needed for future Europa missions (Johnson et al., 1998).

Europa's O_2 atmosphere was first predicted following experiments on the energetic ion irradiation of ice (Johnson et al., 1982; Johnson, 1990). The source of the oxygen is the decomposition of Europa's icy surface by energetic ions trapped in Jupiter's magnetosphere forming H_2, which escapes, and O_2, which remains gravitationally bound to Europa (Johnson et al., 2004). The atmosphere also contains atomic oxygen, formed mainly through the dissociation of O_2, and sputtered trace elements such as sodium. New observing technologies have made the detection of oxygen near Europa's surface possible (Hall et al., 1995). The flux ratio of the 1356 and 1304 Å emission lines suggests that the emission results from the electron impact dissociation of O_2 which leaves one oxygen atom in an excited state.

Although most of the material in the atmosphere remains close to Europa's surface, a portion is ejected with sufficient energy to escape, forming a neutral cloud orbiting Jupiter. The sodium component was first observed by Brown and Hill (1996). Later observations (Brown, 2001) measured the distribution of sodium and potassium within $\sim 40 R_E$ of Europa. The Na/K abundance ratio implies a local source of sodium, possibly from a salty sub-surface ocean, or an extra-jovian source from micro-meteorites, rather than the implantation of iogenic material (Johnson et al., 2002). Recently reported observations by Galileo, coupled with measurements made by Cassini during its flyby of Jupiter, are suggestive of the water product component (Schreier et al., 1993). Lagg et al. (2003) reported the depletion of protons with pitch angle of 90° near Europa which suggests the presence of an equatorially confined cloud of neutral gas. Mauk et al. (2003) detected energetic neutrals, most likely hydrogen, resulting from charge exchange between protons and the Europa neutral cloud, and Hansen et al. (2004) made direct UV observations of oxygen and hydrogen.

In this paper we model the extent and morphology of Europa's neutral sodium cloud and show that its shape is significantly different from the well observed sodium cloud which leads Io in its orbit. Because the radial variation in the ionization rate near Europa is different from that near Io, the cloud at Europa is primarily a trailing cloud. The leading cloud at Europa is greatly reduced compared to the leading cloud at Io.

Because the radial variations in lifetime of the major components of the neutral clouds (O_2, H_2, and O) are similar to the variations in sodium lifetime, sodium should be representative of the distributions of the more abundant species. As these are extremely difficult to observe from Earth and their emissions present large ambiguities due to the highly variable plasma conditions, sodium presents the brightest and least ambiguous view of Europa's neutral cloud.

2. Modeling the sodium clouds

Because similar physical processes create the Europa and Io neutral clouds, models which have been used to study Io's neutrals are readily ap-

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plied to Europa. The model described here is an extension of the model of Wilson and Schneider (1999) which has previously been used to describe such Iogenic features as the fast sodium directional feature (Wilson and Schneider, 1999; Burger et al., 1999), the molecular ion stream (Wilson and Schneider, 1994), and Io's sodium corona (Burger, 2003). We replaced Io's gravitational acceleration with Europa's and used the relevant plasma parameters and velocity distribution. To simulate the creation of the neutral clouds and their loss by ionization into the plasma torus, a particle approach is used to follow atoms ejected from Europa's surface. Packets representing a number of atoms are subjected to the forces of Europa's gravity, Jupiter's gravity, and solar radiation pressure which acts on sodium. Ionization reduces the number of atoms that packets represent. The starting positions and velocities of the packets are randomly chosen based on distributions which are supplied. For these simulations, the initial positions and ejection directions are isotropically distributed over Europa's surface. Starting times are uniformly distributed between the beginning and ending times of the model run, simulating a continuous source from the surface.

Material sputtered from Europa's icy surface provides the material for the neutral clouds. Leblanc et al. (2002) determined the sputtering rate and energy distribution from the surface by modeling observations of the sodium cloud within $\sim 40 R_E$ of Europa. These authors concluded that the velocity distribution of sputtered neutrals is similar to the modified sputtering velocity distribution described by Smyth and Combi (1988) with a most probable speed of $0.7\ \mathrm{km\,s^{-1}}$ and a total sputtering rate of $3 \times 10^7\ \mathrm{atoms\,cm^{-2}\,s^{-1}}$. Approximately 40% of this sodium has sufficient velocity to escape from Europa. They used non-isotropic ejection due to the leading/trailing hemisphere differences, but at large distances from Europa the results are less sensitive to the surface distribution.

The sputtered sodium is ionized primarily by impacts with electrons trapped in the jovian magnetosphere; photoionization and charge exchange with Io plasma torus ions are negligible (Smyth and Combi, 1988; Burger, 2003). The local plasma conditions are calculated by approximating Jupiter's magnetic field as an offset tilted dipole. The Io plasma torus, a ring of plasma originating at Io and extending past Europa's orbit, is centered on Jupiter's centrifugal equator, which is tilted 7° relative to the rotational equator. The plasma conditions along the centrifugal equator were determined by Bagenal (1994) based on in situ measurements by the Voyager spacecraft. Off the centrifugal equator, the electron density decreases exponentially along magnetic field lines, which, in the centrifugal equator, are parallel to Jupiter's rotational axis. In addition, a dawn–dusk electric field across the jovian magnetosphere (Barbosa and Kivelson, 1983; Ip and Goertz, 1983) effectively shifts the plasma torus dawnward. The radial oscillation of the plasma torus about the center of Jupiter as a function of magnetic longitude was measured by Schneider and Trauger (1995) and used by Burger (2003) to determine the variability in plasma conditions in the torus. Figure 1 shows the lifetimes in the centrifugal equator of important neutral cloud species as a function of distance from Jupiter. The lifetimes shown represent the minimum values since the electron density is greatest in the centrifugal plane. Because of the offset and tilt of Jupiter's dipole field and the dawn–dusk electric field, the actual lifetime is a function of distance from Jupiter, distance from the centrifugal equator, magnetic longitude, and local time. At Europa's orbital distance, the sodium lifetime varies between 18 and 34 hours. This lifetime is shorter than previous estimates (e.g., Leblanc et al., 2002) due to the larger electron densities we have used. These differences do not affect the general result we report, although they do introduce uncertainties into the resulting sodium densities. Since resonant scattering of sunlight is the primary emission mechanism, these variations affect the neutral density but not the emission intensity for a given cloud morphology.

A model prediction of the morphology of Europa's sodium cloud is given in Fig. 2. The dominant morphological feature of Europa's sodium cloud is that it is a predominantly trailing cloud: the predicted intensity of sodium in the trailing portion of the cloud is greater than in the leading portion. The opposite is true at Io where the leading cloud is brighter and denser than the trailing cloud (e.g., Macy and Trafton, 1975). The morphology of Io's cloud has been explained by Smyth and Combi (1988) as a result of non-uniform ionization by the plasma torus. The material lead-

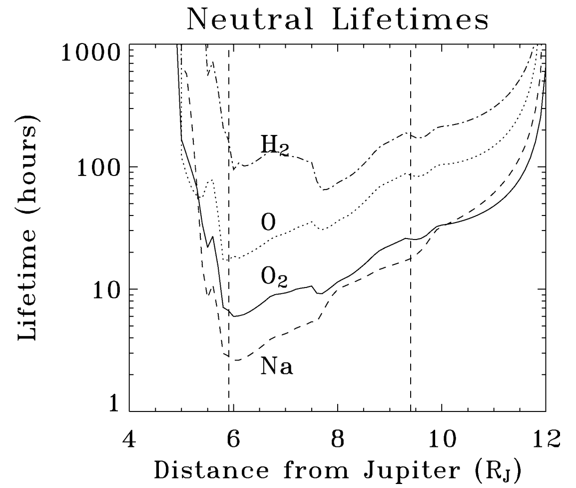

Fig. 1. Average neutral lifetime in the centrifugal plane of major species in Europa's neutral clouds. Sources: Na—Johnston and Burrow (1995); O—McGrath and Johnson (1989), Arnaud and Rothenflug (1985); O_2—Kanik et al. (1993); H_2—Schmidt et al. (1988).

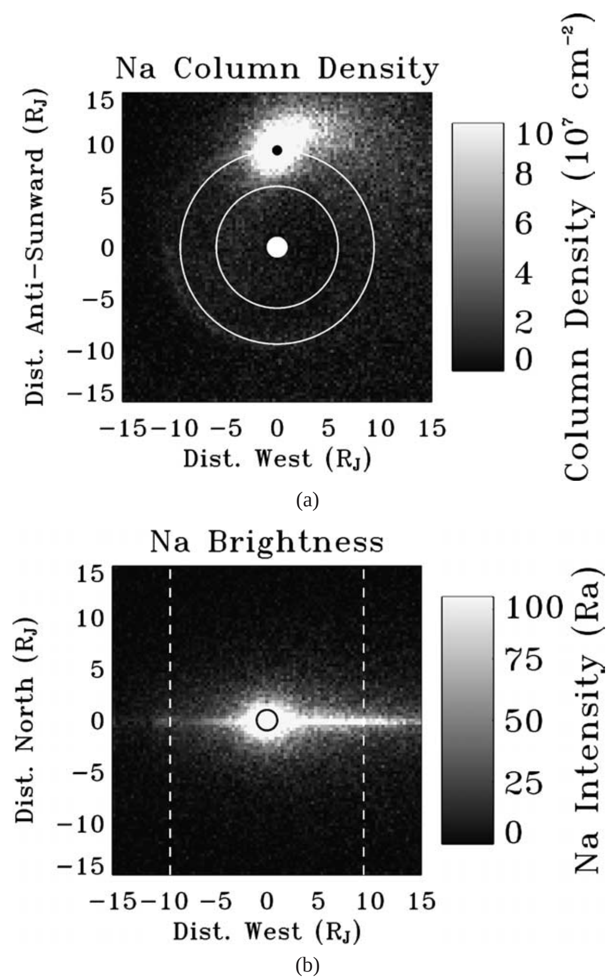

Fig. 2. (a) Modeled sodium column density viewed from above Jupiter's north pole. Circles indicate the locations of Io's and Europa's orbits. Europa (black dot) is behind Jupiter. (b) Modeled sodium intensity viewed from Earth. Broken lines indicate Europa's orbital distance. The thick circle at the origin represents Jupiter with Europa behind.

ing the satellite is interior to its orbit; the trailing cloud contains primarily material exterior to the satellite orbit. Because the sodium lifetime interior to Io's orbit is longer than exterior, sodium atoms in the leading cloud survive longer, resulting in the brighter leading cloud. At Europa, the lifetime structure is reversed (Fig. 1) so a trailing cloud is formed. Therefore, the morphology revealed through observations will provide a means to study radial variations in the plasma conditions near Europa.

To test the importance of radial variations in lifetime on the morphology of the sodium cloud, we modeled the cloud using three sodium lifetime profiles (Fig. 3). In the "Europa-like" case, the lifetime is approximated by an exponential fit to the average sodium lifetime predicted from electron impacts. The "Io-like" case uses a decreasing lifetime with distance. A constant lifetime case was also modeled. The effects of the oscillating plasma torus and the dawn–dusk electric field have not been included in these simulations. Because Europa is behind Jupiter for these model simulations, the leading cloud extends east and the trailing cloud extends west. The Europa-like case results in a bright trailing cloud with no leading cloud and the Io-like case produces a bright leading cloud with no trailing cloud. A constant lifetime produces a more symmetric cloud about Europa. The increase in intensity in the Europa-like case east of Jupiter but outside of Europa's orbital distance ($9.4R_J$) results from the sharp increase in sodium lifetime outside of $12R_J$ that is used in this simulation.

This predicted morphology is roughly consistent with that found in Leblanc et al. (2002) who focused on sodium closer to Europa. Model predictions by these authors suggest an enhancement of the trailing cloud. However, the observations they reported show a smaller east/west asymmetry. Several factors may contribute to this difference. The scale of their observations (within $\sim 40R_E$ of Europa) is approximately the scale on which we predict the asymmetry to become visible. A longer sodium lifetime consistent with lower electron densities would increase this length scale so that it would be necessary to observe farther from Europa to detect an asymmetry. In addition, they assumed an enhanced sputtering flux from Europa's upstream (trailing) hemisphere so that more sodium is ejected into the leading cloud, partially offsetting the increased ionization rate. Detailed comparisons between models and observations can eventually help constrain the source regions.

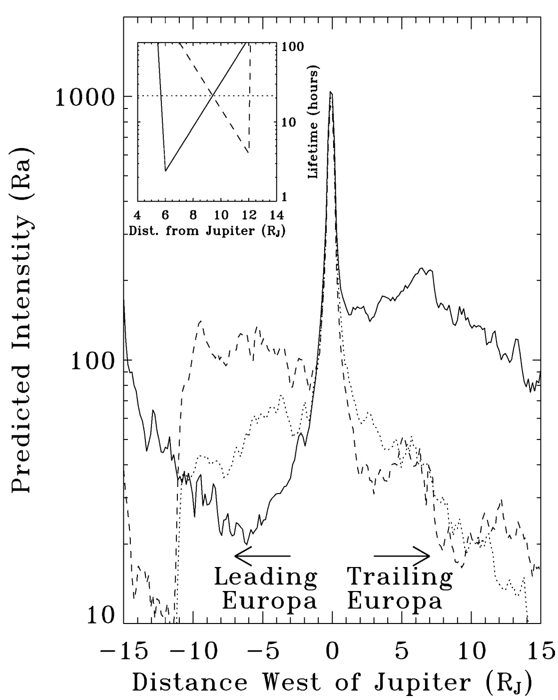

Fig. 3. Modeled sodium brightness in Europa's orbital plane as function of distance from Jupiter. The solid line shows a model with the sodium lifetime increasing with distance from Jupiter; the broken line is a model with lifetime decreasing with distance, and the dotted model used a constant lifetime. The neutral lifetime for each case is shown in the insert.

3. Discussion and conclusions

Observations of Europa's sodium cloud should reveal large scale morphological differences from the Io sodium cloud; namely, the trailing cloud will be much brighter and more extensive than the leading cloud. This conclusion is valid if (a) the sodium ionization rate decreases with distance from Jupiter as is expected from the Voyager measurements, and (b) the sputtering of sodium from Europa's surface ejects as much material into the trailing cloud as into the leading cloud. Preferential energetic ion bombardment on the trailing hemisphere may not be consistent with this condition and could explain the lack of an east/west asymmetry in the sodium emission near Europa.

The sodium distribution should serve as an excellent tracer of the other species lost from Europa's atmosphere. The O_2 and sodium lifetimes, in particular, are very similar despite different destruction mechanisms (Fig. 1). Sodium is ionized by electron impact ionization. The O_2 lifetime is determined by both electron impact ionization and electron impact dissociation. Although the initial energy distributions of the two species are different, the overall morphology of the cloud is relatively insensitive to these differences. The sodium morphology also provides insight into the distributions of molecular hydrogen and atomic oxygen, although the lifetimes of these species are expected to be longer resulting in a more uniform distribution of neutrals similar to the constant lifetime case in Fig. 3. A detailed discussion of the distributions of these species will be the focus of a future paper.

Our model of the sodium cloud shows large variations in density with both jovian local time relative to Europa and radial distance from Jupiter. Mauk et al. (2003) and Lagg et al. (2003) observed a component of the Europa cloud and inferred neutral densities of 20–50 and $\sim 40\ \mathrm{cm}^{-3}$, respectively, assuming uniform tori centered at Europa's orbital distance. These are predominately hydrogen atoms (Shematovich et al., 2004) which have a longer lifetime than sodium. This is confirmed by Hansen et al. (2004) who observed the escaping component of the oxygen atmosphere, but failed to detect it far from Europa despite having detection limit lower than the densities predicted. Our average density in this region is ~ 5–10×10^{-3} atoms cm^{-3}, assuming that the sodium surface mixing ratio of 0.5–1% (Johnson, 2000) is maintained by the escaping neutrals. In the portion of the cloud between 9.4 and $14.4R_J$ from Jupiter, where we show most of the neutrals residing, Mauk et al. estimated a total neutral content of 4.5×10^{33} atoms and molecules. The equivalent hydrogen source rate from our model would give a total torus content $> 10^{35}$ atoms and molecules. An analysis of the consistency between the neutral distribution we have determined and the Cassini and Galileo observations is beyond the scope of this work, but these instruments were more sensitive neutrals outside Europa's orbit; densities inside Europa's orbit were extrapolations from their data.

Observations of sodium emission have advantages over observations of emissions from the more abundant species which make it the most promising candidate for determining the morphology and structure of Europa's extended neutral clouds. The most important advantage is that the sodium cloud is the brightest component. At Europa's surface, the Na/O brightness ratio is ~ 200 (Brown, 2001; Hall et al., 1995). Far from Europa, where brightnesses are reduced by several orders of magnitude, sodium may be the only species bright enough to observe, although separating the emissions from the Io neutral cloud will pose significant difficulties (e.g., Leblanc et al., 2002).

The interpretation of sodium emissions is also much less ambiguous than oxygen emissions. The sodium brightness depends only on the column density of sodium and the incident solar flux; it is insensitive to the local plasma conditions. The observed oxygen transitions at 1304 and 1356 Å are primarily excited through electron impact on O or the electron impact dissociation of O_2 which are highly dependent on the local plasma. The Galileo spacecraft recorded electron densities between 18 and 250 cm^{-3} in the vicinity of Europa (Kivelson et al., 2004); variations in electron density with magnetic longitude, time, and location in Jupiter's equatorial plane are not well constrained. Unless simultaneous measurements of the plasma are made, emission rates and oxygen density cannot be precisely determined. In addition, it will be difficult to determine the relative abundances of atomic and molecular oxygen from atomic oxygen emissions.

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